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Three-Phase Cascaded H-Bridge Multilevel PV Inverter for Reducing Harmonics by using PI and Fuzzy Logic Controller

G.Ujwala,
Assistant professor, Department of EEE,
G. Narayanamma Institute Of Technology And Science,

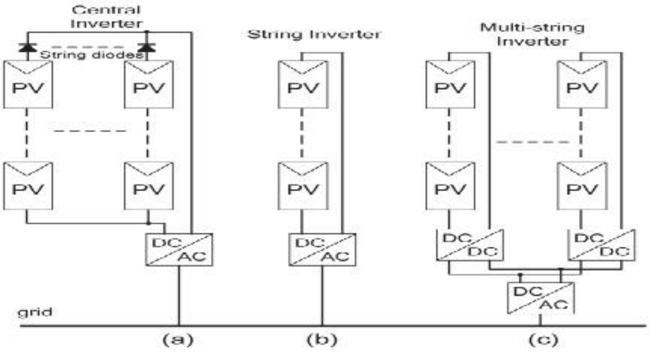
V.Rashmi,
P.G Scholar, Department of EEE
G. Narayanamma Technology And Science,

Abstract: This paper presents three-phase cascaded multilevel topology helps in reduction of harmonic distortion which improves the efficiency and flexibility of PV systems. To realize better utilization of PV modules and maximize the solar energy extraction, a distributed maximum power point tracking control scheme is applied to three-phase multilevel inverters, which allows independent control of each DC-link voltage. Due to different irradiance conditions, PV mismatches may introduce unbalanced supplied power, leading to unbalanced grid current. To solve this issue, a control scheme with modulation compensation is also proposed. This modulation compensation is built with pi controller and fuzzy logic controller in order to reduce total harmonic distortion (THD) which improves efficiency. Simulation results are presented to verify the feasibility of the proposed approach.

Keywords: Cascaded Multilevel Inverter, Maximum Power Point Tracking (MPPT), PI Controller, Fuzzy Logic Controller, Modulation Compensation, Photovoltaic (PV).

I. INTRODUCTION

Due to the shortage of fossil fuel, Solar-electric-energy demand has grown consistently by 20%–25% per annum over the past 20 years, and the growth is mostly in grid-connected applications. With the extraordinary market growth in grid-connected photovoltaic (PV) systems, there are increasing interests in grid-connected PV configurations. Five inverter families can be defined, which are related to different configurations of the PV system: 1) central inverters; 2) string inverters; 3) multi string inverters; 4) ac-module inverters; and 5) cascaded inverters. The configurations of PV systems are shown in Fig. 1. Cascaded inverters consist of several converters connected in series; thus, the high power and/or high voltage from the combination of the multiple modules would favor this topology in medium and large grid-connected PV systems. There are two types of cascaded inverters. Fig. 1(e) shows a cascaded dc/dc converter connection of PV modules. Each PV module has its own dc/dc converter, and the modules with their associated converters are still connected in series to create a high dc voltage, which is provided to a simplified dc/ac inverter. This approach combines aspects of string inverters and ac-module inverters. However, there are two power conversion stages in this configuration. Another cascaded inverter is shown in Fig. 1(f), where each PV panel is connected to its own dc/ac inverter, and those inverters are then placed in series to reach a high-voltage level.



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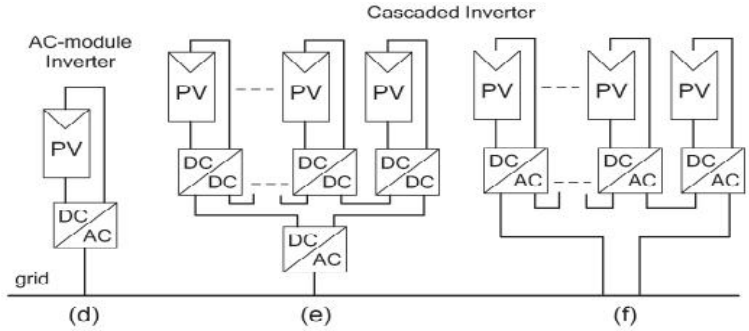

Fig.1: Configurations of PV systems. (a) Central inverter. (b) String inverter.
(c) Multi string inverter. (d) AC-module inverter., (e) Cascaded dc/dc converter. (f) Cascaded dc/ac inverter

II. SYSTEM DESCRIPTION

Modular cascaded H-bridge multilevel inverters for single and three-phase grid-connected PV systems are shown in Fig. 2. Each phase consists of *n* H-bridge converters connected in series, and the dc link of each H-bridge can be fed by a PV panel or a short string of PV panels. The cascaded multilevel inverter is connected to the grid through *L* filters, which are used to reduce the switching harmonics in the current. By different combinations of the four switches in each H-bridge module, three output voltage levels can be generated: $-v_{dc}$, 0, or $+v_{dc}$. A cascaded multilevel inverter with *n* input sources will provide $2n + 1$ levels to synthesize the ac output waveform. This $(2n + 1)$-level voltage waveform enables the reduction of harmonics in the synthesized current, reducing the size of the needed output filters. Multilevel inverters also have other advantages such as reduced voltage stresses on the semiconductor switches and having higher efficiency when compared to other converter topologies.

III. PANEL MISMATCHES

PV mismatch is an important issue in the PV system. Due to the unequal received irradiance, different temperatures, and aging of the PV panels, the MPP of each PV module may be different. If each PV module is not controlled independently, the efficiency of the overall PV system will be decreased. To show the necessity of individual MPPT control, a five-level two-H-bridge single-phase inverter is simulated in MATLAB/SIMULINK. Each H-bridge has its own 185-W PV panel connected as an isolated dc source. Consider an operating condition that each panel has a different irradiation from the sun; panel 1 has irradiance *S* =1000 W/m2, and panel 2 has *S* = 600 W/m2. .when the *S* values are 1000 and 600 W/m2, respectively, which means that the total power harvested from the PV system would be 293.5 W if individual MPPT can be achieved. This higher value is about 1.45 times of the one before. For example, to unbalance the current per phase more than 10% is not allowed for some utilities, where the percentage imbalance is calculated by taking the maximum deviation from the average current and dividing it by the average current.

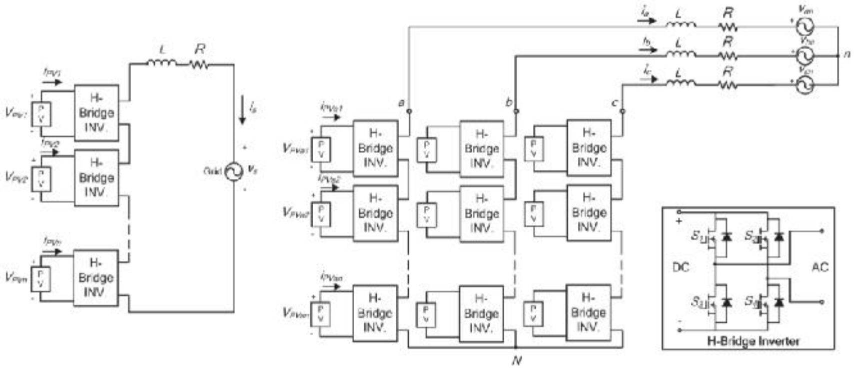

Fig.2. Topology of the modular cascaded H-bridge multilevel inverter for grid-connected PV

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IV. CONTROL SCHEME

A. Distributed MPPT Control

In order to eliminate the adverse effect of the mismatches and increase the efficiency of the PV system, the PV modules need to operate at different voltages to improve the utilization per PV module. The separate dc links in the cascaded H-bridge multilevel inverter make independent voltage control possible. The distributed MPPT control of the three-phase cascaded H-bridge inverter is shown in Fig. 4. In each H-bridge module, an MPPT controller is added to generate the dc-link voltage reference. Each dc-link voltage is compared to the corresponding voltage reference through proportional-integral (PI) controller and the sum of all errors is controlled through a total voltage controller (i.e.,) fuzzy logic controller that determines the current reference I_{dref}. The reactive current reference I_{qref} can be set to zero, or if reactive power compensation is required, I_{qref} can also be given by a reactive current calculator. The synchronous reference frame phase-locked loop (PLL) has been used to find the phase angle of the grid voltage. As the classic control scheme in three-phase systems, the grid currents in abc coordinates are converted to dq coordinates and regulated through proportional–integral (PI) controllers to generate the modulation index in the dq coordinates, which is then converted back to three phases.. The fuzzy logic controller gives the magnitude of the active current reference, and a PLL provides the frequency and phase angle of the active current reference. The current loop then gives the modulation index. To make each PV module operate at its own MPP, take phase a as an example; the voltages v_{dca2} to v_{dcan} are controlled individually through n − 1 loops. Each voltage controller gives the modulation index proportion of one H-bridge module in phase a. After multiplied by the modulation index of phase a, n − 1 modulation indices can be obtained. Also, the modulation index for the first H-bridge can be obtained by subtraction. The control schemes in phase’s b and c are almost the same. The only difference is that all dc-link voltages are regulated through PI controllers, and n modulation index proportions are obtained for each phase. The total voltage controller used in this circuit fuzzy logic controller which helps in improvement in total harmonic distortion (THD).Design of a fuzzy controller requires more design decisions than usual, for example regarding rule base, inference engine, defuzzification, and data pre- and post process.

Table 1. Fuzzy rule base

$\Delta e(r)$ \ $e(r)$ (u)	N	Z	P
N	b	b	b
Z	-b	0	b
P	-b	-b	-b

Fig: 3 Fuzzy logic controllers.

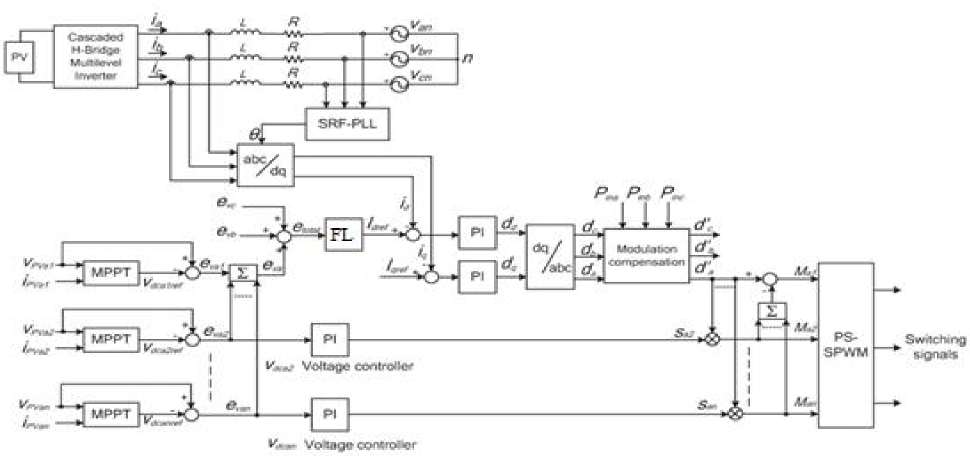

Fig.4. Control scheme for three-phase modular cascaded H-bridge multilevel PV inverter

A phase-shifted sinusoidal pulse width modulation switching scheme is then applied to control the switching devices of each H-bridge. It can be seen that there is one H-bridge module out of N modules whose modulation index is obtained by subtraction. For three-phase systems, $N = 3n$, where n is the number of H-bridge modules per phase. The reason is that N voltage loops are necessary to manage different voltage levels on N H-bridges, and one is the total voltage loop, which gives the current reference. So, only $N - 1$ modulation indices can be determined by the last $N - 1$ voltage loops, and one modulation index has to be obtained by subtraction. The incremental conductance method has been used in this paper. It lends itself well to digital control, which can easily keep track of previous values of voltage and current and make all decisions.

B. Modulation Compensation

As mentioned earlier, a PV mismatch may cause more problems to a three-phase modular cascaded H-bridge multilevel PV inverter. With the individual MPPT control in each H-bridge module, the input solar power of each phase would be different, which introduces unbalanced current to the grid. To solve the issue, a zero sequence voltage can be imposed upon the phase legs in order to affect the current flowing into each phase. If the updated inverter output phase voltage is proportional to the unbalanced power, the current will be balanced. Thus, the modulation compensation block, as shown in Fig. 5, is added to the control system of three-phase modular cascaded multilevel PV inverters.

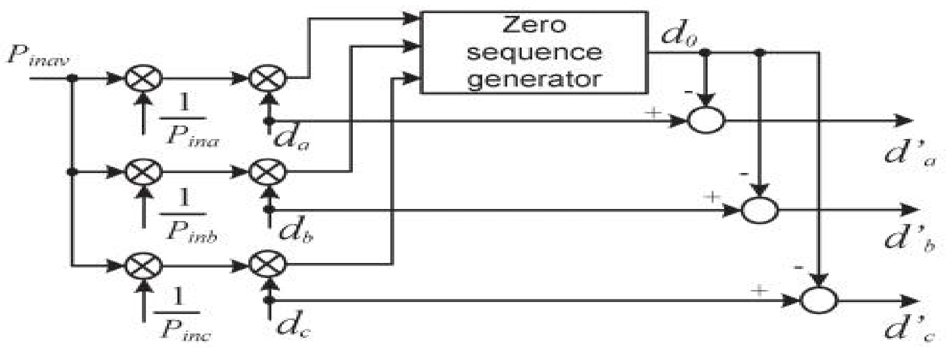

Fig.5. Modulation compensation scheme

First, the unbalanced power is weighted by ratio r_j, which is calculated as

$$r_j = \frac{P_{inav}}{P_{inj}} \quad (1)$$

Where P_{inj} is the input power of phase j (j = a, b, c), and P_{inav} is the average input power. Then, the injected zero sequence modulation indexes can be generated as

$$d_0 = \frac{1}{2}\left[\min(r_a \cdot d_a, r_b \cdot d_b, r_c \cdot d_c) + \max(r_a \cdot d_a, r_b \cdot d_b, r_c \cdot d_c)\right] \quad (2)$$

Where d_j is the modulation index of phase j ($j = a, b, c$) and is determined by the current loop controller. The modulation index of each phase is updated by

$$d_j' = d_j - d_0 \quad (3)$$

Assume that the input power of each phase is unequal

$$P_{ina} = 0.8 \qquad P_{inb} = 1 \qquad P_{inc} = 1 \quad (4)$$

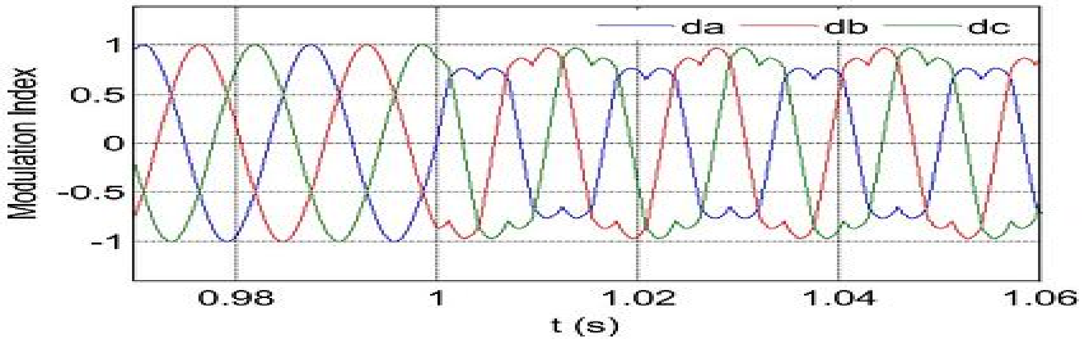

Fig.6: Modulation indices before and after modulation compensation.

By injecting a zero sequence modulation index at t = 1 s, the balanced modulation index will be updated, as shown in Fig. 6. It can be seen that, with the compensation, the updated modulation index is unbalanced proportional to the power, which means that the output voltage ($v\ j\ N$) of the three-phase inverter is unbalanced, but this produces the desired balanced grid current.

V. SIMULATION RESULTS

Simulation tests are carried out to validate the proposed ideas. Each H-bridge has its own 185-W PV panel. The inverter is connected to the grid through a transformer, and the phase voltage of the secondary side is 60 V_{rms}. The system parameters are shown in Table 2.

TABLE 2:
SYSTEM PARAMETERS

Parameters	Value
DC-link capacitor	3600 µF
Connection inductor L	2.5 mH
Grid resistor R	0.1 ohm
Grid rated phase voltage	60 Vrms
Switching frequency	1.5 kHz

To verify the proposed control scheme, the three-phase grid connected PV inverter is simulated in two different conditions. First, all PV panels are operated under the same irradiance S = 1000 W/m2 and temperature T = 25 ◦C. At t = 0.8 s, the solar irradiance on the first and second panels of phase a decreases to 600 W/m2, and that for the other panels stays the same. The dc-link voltages of phase a are shown in Fig. 7. At the beginning, all PV panels are operated at an MPP voltage of 36.4 V. As the irradiance changes, the first and second dc link voltages decrease and track the new MPP voltage of 36 V, while the third panel is still operated at 36.4 V. The PV current waveforms of phase a are shown in Fig. 8. After t = 0.8 s, the currents of the first and second PV panels are much smaller due to the low irradiance, and the lower ripple of the dc-link voltage can be found in Fig. 7 (a). The dc-link voltages of phase b are shown in Fig. 9. All phase-b panels track the MPP voltage of 36.4 V, which shows that they are not influenced by other phases. The connected PV panel of each H-bridge can be operated at its own MPP voltage and will not be influenced by the panels connected to other H-bridges. Thus, more solar energy can be extracted, and the efficiency of the overall PV system will be increased. Fig. 10 shows the power extracted from each phase. At the beginning, all panels are operated under irradiance S = 1000 W/m2

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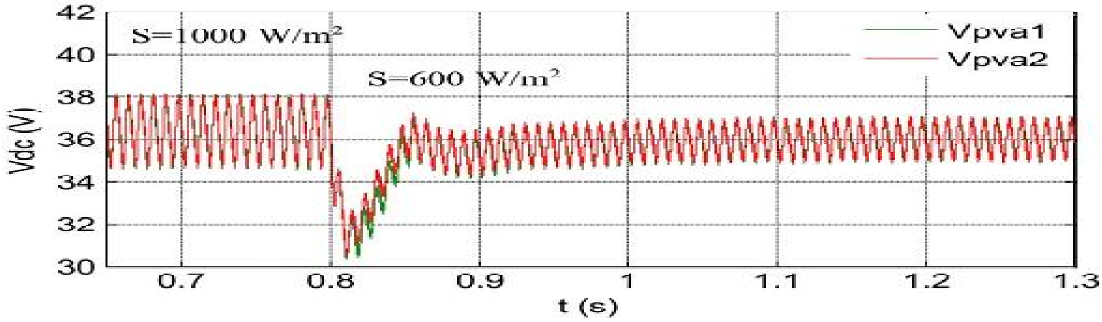
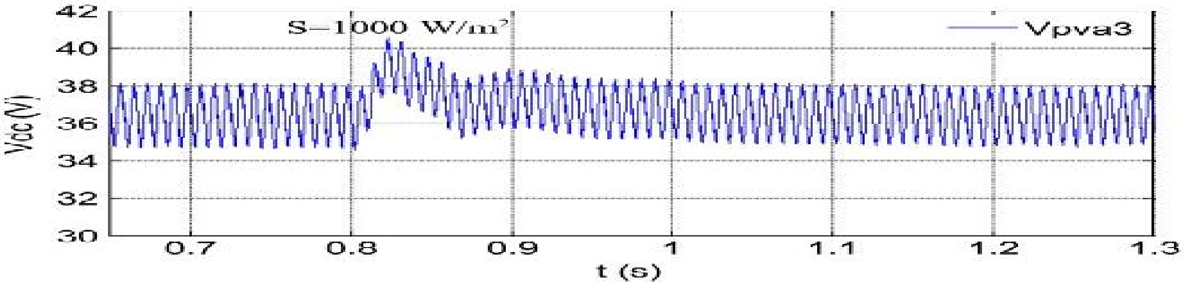


(a)



(b)

Fig. 7: DC-link voltages of phase *a* with distributed MPPT (T = 25 ◦ C). (a) DC-link voltage of modules 1 and 2. (b) DC-link voltage of module 3.

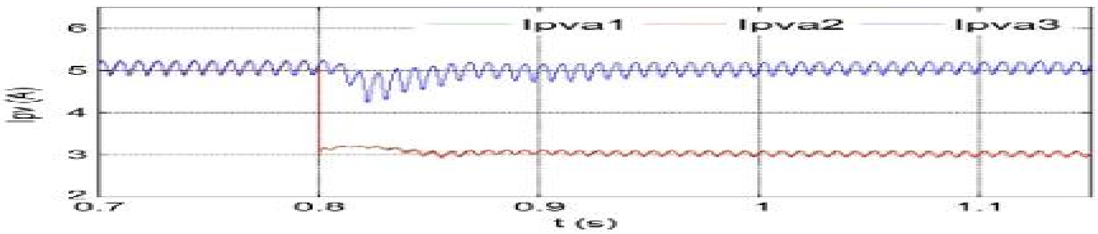


Fig. 8: PV currents of phase *a* with distributed MPPT (T = 25 ◦ C)

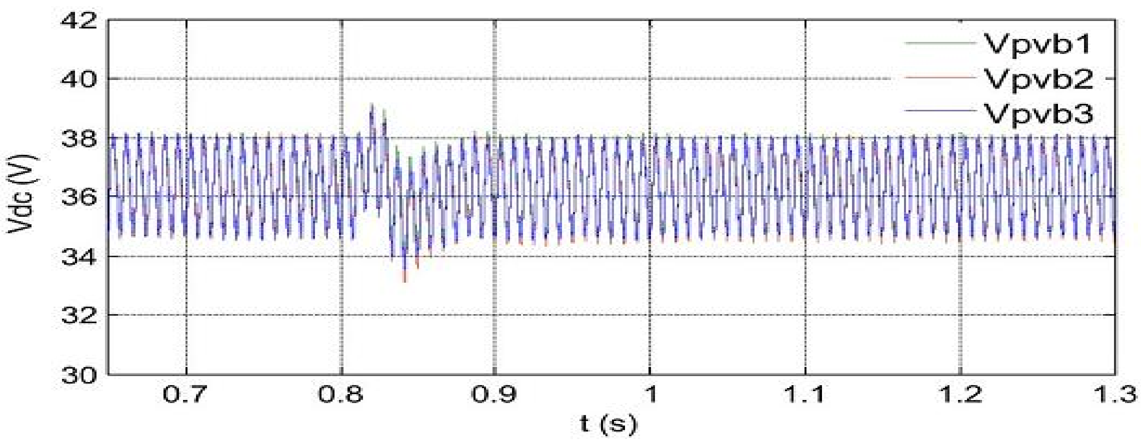


Fig.9: DC-link voltages of phase *b* with distributed MPPT (*T* = 25 ◦ C).

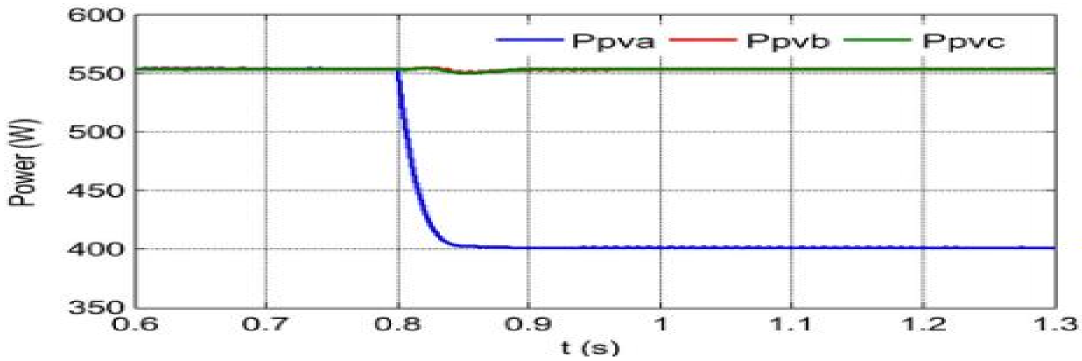


Fig. 10: Power extracted from PV panels with distributed MPPT.

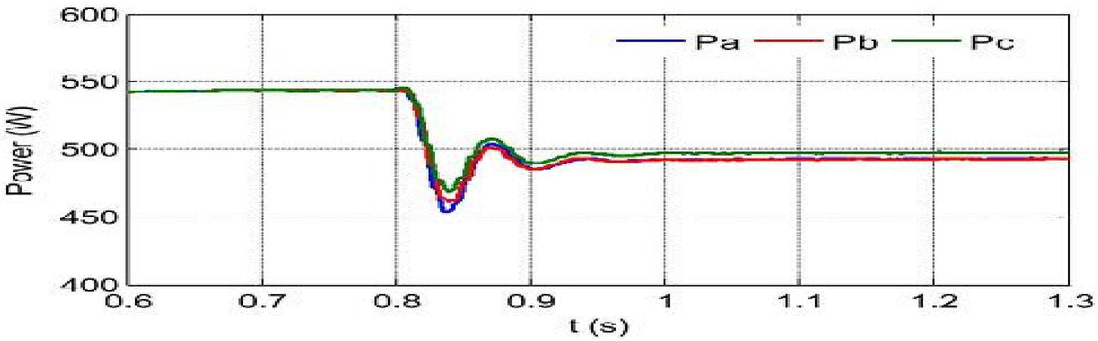


Fig.11: Power injected to the grid with modulation compensation

and every phase is generating a maximum power of 555 W. After t = 0.8 s, the power harvested from phase a decreases to 400 W, and those from the other two phases stay the same. Obviously, the power supplied to the three-phase grid-connected inverter is unbalanced. However, by applying the modulation compensation scheme, the power injected to the grid is still balanced, as shown in Fig. 11. In addition, by comparing the total power extracted from the PV panels with the total power injected to the grid, it can be seen that there is no extra power loss caused by the modulation compensation scheme. Fig. 12 shows the output voltages (v j N) of the three-phase inverter. Due to the injected zero sequence component, they are unbalanced after t = 0.8 s, which help to balance the grid current shown in Fig. 13.

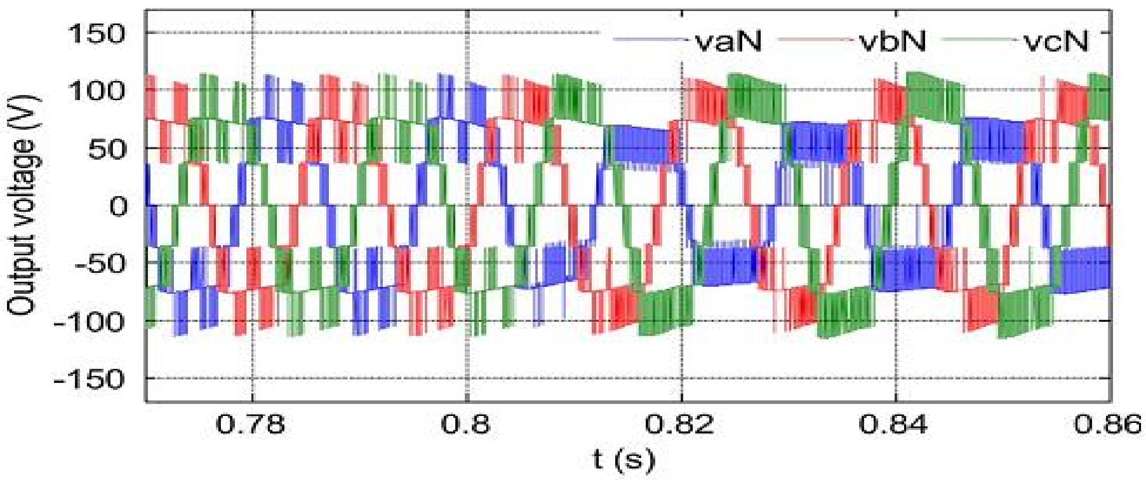


Fig.12. Three-phase inverter output voltage waveforms with modulation compensation

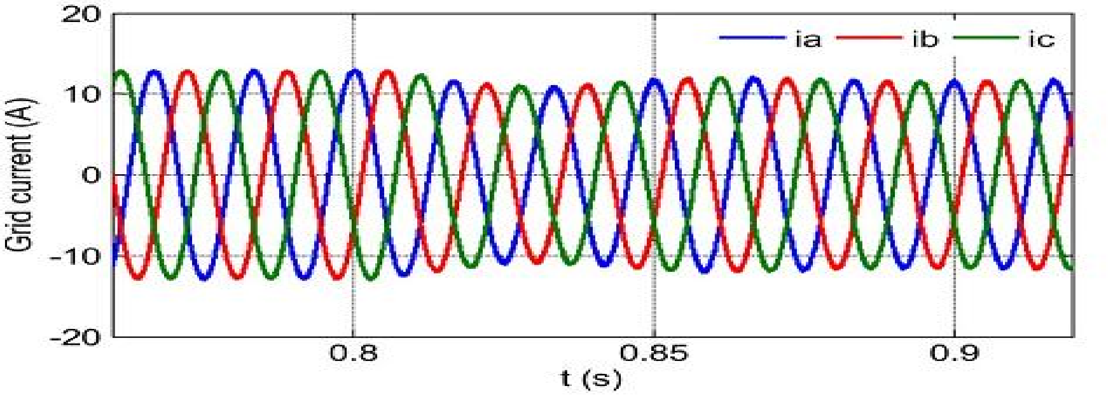


Fig.13. Three-phase grid current waveforms with modulation compensation

The total harmonic distortion (THD) of grid current shown in below fig.14 is 3.3% after fuzzy logic controller THD reduces to 2.5%, which is less than 5% and meets power quality standards, like IEEE 1547 in the U.S. and IEC 61727 in Europe.

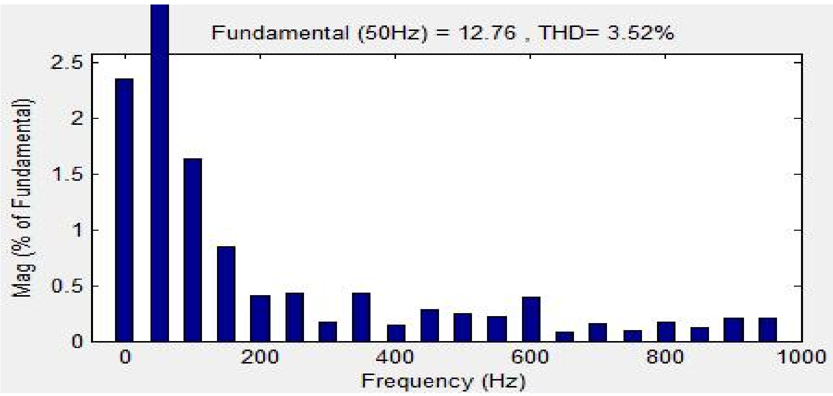


Fig .14: Total harmonic distortion without fuzzy logic controller

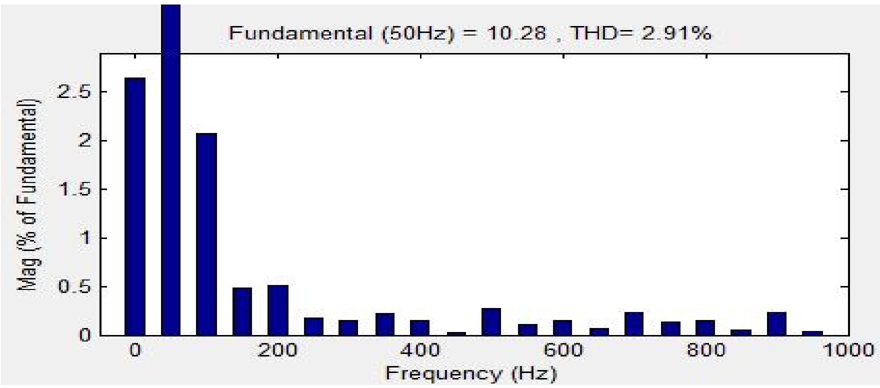


Fig .15: Total harmonic distortion with Fuzzy logic controller

VI. CONCLUSION

In this paper, a three-phase cascaded H-bridge multilevel PV inverter harmonic distortion with PI and fuzzy logic controller has been presented. The multilevel inverter topology will help to improve the utilization of connected PV modules if the voltages of the separate dc links are controlled independently. Thus, a three-phase PV system has been applied to increase the overall efficiency of PV systems. For the three-phase grid-connected PV system, PV mismatches may introduce unbalanced supplied power, resulting in unbalanced

injected grid current. A modulation compensation scheme, which will not increase the complexity of the control system or cause extra power loss, is added to balance the grid current. With the proposed control scheme, each PV module can be operated at its own MPP to maximize the solar energy extraction, and the three-phase grid current is balanced even with the unbalanced supplied solar power.

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